ATU-DSS: Knowledge-Driven Data Integration and Reasoning for Sustainable Subsurface Inter-Asset Management

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Abstract. Urban infrastructure assets perform critical functions to the health and well-being of the society. In this paper, we present a prototype decision support system for sustainable subsurface inter-asset management. To the best of the authors' knowledge, this work is the first on assessing the underground space by considering the inter-asset dependencies using semantic technologies. Based on a family of interlinked city infrastructure asset ontologies describing the ground, roads and buried utilities (e.g. water pipes), various datasets are integrated and logical rules are developed to describe the intra-asset and inter-asset relationships. An inference engine is employed to exploit the knowledge and data for assessing the potential impact of an event. This system can be beneficial to a wide range of stakeholders (e.g. utility incident managers) for quickly gathering of the localised contextual data and identifying potential consequences from what may appear as an insignificant trigger. A video demonstrating the prototype is available at: `http://bit.ly/2mdyIY4`.

Keywords: Semantic technologies, ontologies, decision support system, subsurface infrastructure, sustainable streetworks

1 Introduction

The Assessing The Underworld (ATU) project[1] is a large interdisciplinary UK research programme that aims to address the challenges in sustainable management and maintenance of city infrastructure assets, especially how to reduce the economic, social and environmental costs/impact of streetworks. It is estimated that the direct costs of streetworks to local authorities are about £50M/year in the UK[2]. A consultation meeting with stakeholders (local authorities, utility companies of water/gas/electricity/sewage/communications, asset managers, traffic managers, consultants, contractors, ground engineers, testing houses) was organized at the start of the ATU project and several key challenges to sustainable streetworks in practice were identified: urban infrastructure assets, such as

[1] `http://assessingtheunderworld.org/`
[2] Asphalt Industry Alliance (2017) Annual Local Authority Road Maintenance

roads, ground and subsurface utilities are maintained by different stakeholders who plan and conduct streetworks independently; relevant infrastructure data is held by different owners and difficult to gather in a short period of time; moreover, lack of the knowledge of dependencies between different infrastructure assets makes it difficult for decision makers from one sector to consider the impact/damage of their actions on other nearby infrastructure assets [1]. For example, breaking up or opening a road can damage the ground and the buried utilities [6]. A leaking water pipe can erode the surrounding ground, leading to loss of support to the overlying road and eventually causing road collapse [1].

In order to address these challenges, we present a prototype decision support system (**A**ssessing **T**he **U**nderworld **D**ecision **S**upport **S**ystem or **ATU-DSS**) for subsurface inter-asset management using semantic technologies. It can assist practitioners (e.g. junior engineers) in making decisions about the impact of a trigger (e.g. planned works, loss of water pressure) with respect to its localised contextual data and its influence on different infrastructure assets. While semantic approaches have been used to manage infrastructure in several project[3], this paper gives insights into the exploitation of semantic technologies in a new domain with high economic and societal importance - the underground world.

In the following sections, we first describe the system architecture of the ATU-DSS (Section 2). We then provide a general description of the demo from a user's perspective (Section 3).

2 System Components of the ATU-DSS

At the heart of the ATU-DSS is an integrated knowledge model of urban infrastructure assets, which was developed by consulting with domain experts (e.g. civil engineers, geotechnical engineers, geophysicists) in the project and extensively reviewing literature. This knowledge model consists of several interlinked modular ontologies which are referred to as *ATU ontologies*. The *ATU City Infrastructure Asset Ontologies* [2,3] define the properties and processes of the ground, roads and buried utilities (publicly available at `https://doi.org/10.5518/190`). The *ATU Trigger Ontology* defines the categories and properties of events (e.g. *WaterPipeObservation_LossOfPressure*) that require some decisions to be made in subsurface infrastructure asset management [1]. The *ATU Investigation Ontology* encodes the knowledge of the available geophysical techniques for measuring different asset properties in shallow (0-5m depth) streetworks surveys. The *ATU Environment Ontology* models the environment factors (e.g. rainfall, drought) affecting or being affected by the infrastructure assets based on several existing external ontologies (e.g. NASA's SWEET Ontology[4], the Environment Ontology[5], Ordnance Survey's Buildings and Places Ontology[6]). The ATU ontologies provide a common vocabulary for defining inference rules and integrating various datasets such that heterogeneous data can be used together in automated reasoning. For example, a rule *"Heavy and Long rainfall*

[3] *INTERLINK*: `https://roadotl.geosolutions.nl/`; *Coinsweb* (Construction Objects and the INtegration of Processes and Systems): `http://www.coinsweb.nl/`

[4] `https://sweet.jpl.nasa.gov/`

[5] `http://environmentontology.org/`

[6] `http://bit.ly/2Fq5u0F`

will infiltrate the road if the road crack penetrates the road surface." is defined referring to the concepts in the *Environment Ontology* and the *Road Ontology* (see Figure 2a), written as: "*EnvironmentRainfallIntensity (Heavy) + EnvironmentRainfallDuration (Long) + RoadCrackingDepth (High)* $\xrightarrow{(definite)}$ *RoadWaterInfiltration (Active)*". Three scenarios have been considered when defining rules: rainfall with road cracking, pipe leakage and traffic overloading. The rule engine *Jess*[7] is used for rule development and reasoning, due to scalability reasons, since the reasoning performance of *Jess* depends not much on the number of rules/facts but on the number of partial matches generated by *Jess*. The ATU-DSS is designed using three-tier architecture consisting of a data layer, an application layer and an interface layer. The data layer consists of the ATU ontologies and real-world datasets. Informed by the ATU ontologies, several datasets were sourced from different data owners, including the historic meteorological data (e.g. rainfall, temperature.)[8], the road and historic traffic data[9], the ground condition data from British Geological Survey (BGS) and local councils, the information of buried utilities (e.g. pipe location, age)[10], as well as the information of sensitive population and services (e.g. hospitals, schools) from OpenStreetMap (OSM). Data on the local server is managed by a PostgreSQL database for its advanced support to geo-spatial calculation with PostGIS. OSM data is fetched on-demand with an API. The data layers are mapped to corresponding ontology concepts based on a predefined correspondence table. Some of them can be mapped directly, for example, the "BGS Depth to Groundwater Dataset" is mapped directly to the *GroundWaterTableDepth* concept in the *Ground Ontology*. Other data layers need preprocessing before being linked to ontology concepts. For example, rainfall duration is calculated based on the historical data from nearby weather stations and then mapped to the *EnvironmentRainfallDuration* concept. Currently, all these correspondences are manually defined to guarantee their correctness. We are also working towards automating the matching process by employing existing ontology matching techniques [4].

The application layer is built on the data layer and could suggest potential impacts of a trigger through automated reasoning. The user interface layer is accessible through a standard web browser, which allows decision makers to interact with the DSS such as reporting new triggers, viewing retrieved localised data and examining the inferencing results. The web framework is written with *Python Django (HTML/CSS/Javascript)* and *Geoserver* is used to provide web mapping services.

3 Demonstration of the ATU-DSS

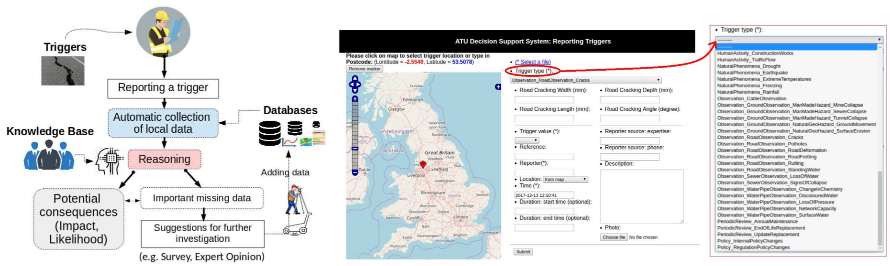
This section will demonstrate how to use the ATU-DSS step by step. A video demonstrating the prototype is available at: `http://bit.ly/2mdyIY4`, using real

[7] `http://www.jessrules.com/jess/docs/71/`

[8] Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). N.B., weather data in the local database is updated at the end of each month; and the 30-day weather data up to the occurrence time of a trigger is shown on the user interface and used for analysis.

[9] UK Department for Transport (DfT) Traffic Statistics (update annually).

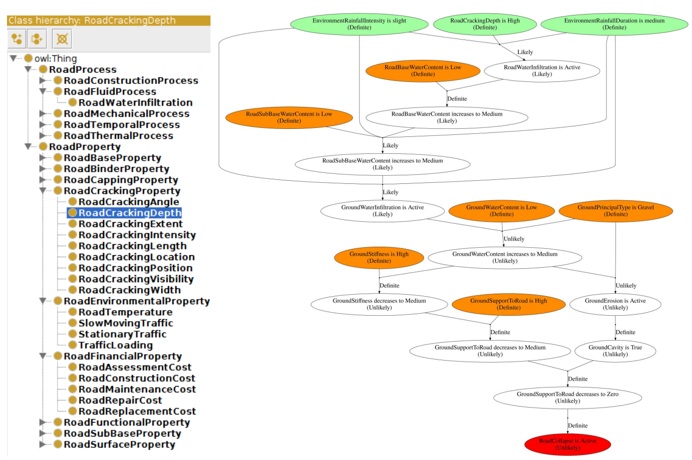
[10] Data in testing regions were sourced from different utility companies.



(a) Workflow of **ATU-DSS** (b) Interface for reporting new triggers

Fig. 1. Workflow of the **ATU-DSS** (left); the interface for reporting triggers (©OSM)

data from a sinkhole happened in Manchester (UK) which caused a major disruption. As shown in Figure 1a, the working procedure of ATU-DSS starts with a report of triggers (defined in the *ATU Trigger Ontology*) through the web interface. Each trigger is attached with a spatial geometry and should be provided by users. Then, the localised contextual data of a reported trigger is automatically retrieved based on its occurrence location and time. The retrieved data is displayed on the user interface and fed into the rule engine for automated reasoning of potential consequences. The uncertainty of facts and rules are also propagated during the reasoning process [5]. Once this process finishes, potential consequences are identified from the inferred facts and presented to users according to their estimated severity and likelihood. The system also gives explanations of potential consequences in the form of text and diagram[11] (e.g. Figure 2b).



(a) *Road Ontology.* (b) Reasoning chain of *Road Collapse*.

Fig. 2. Road ontology and graphic view of the reasoning chain of *RoadCollapse*.

By explaining and visualizing to users the reasoning process of arriving at a particular consequence, the system can help users make a more reasonable and

[11] The diagrams are automatically generated with a python package of Graphviz.

informed decision. In the ATU-DSS, in cases where real data is missing (i.e. default values under worst case assumption are used) in the reasoning process [5], the system will not only remind users of the missing data but also suggest suitable investigation techniques to get the missing data (based on the *ATU Investigation Ontology*). Users can choose to accept the default value or add/update data after some investigation. When new data is added/updated, the whole reasoning process automatically re-activates. The system records which user makes a modification so that the provenance of all data is recorded. The justifications and the ability for users to see how modifying assumptions lead to different consequences can again help users make a more reasonable decision.

4 Conclusion and Future Work

In this work, we presented a prototype of a knowledge-driven decision support system for sustainable subsurface inter-asset management based on a family of urban infrastructure asset ontologies. The prototype includes an integrated geospatial database and an inference engine for assessing of the impact of triggers based on ATU ontologies. As future work, we will continue increasing the rule base by considering more scenarios; we also plan to do more evaluation of the system with more users and historic cases.

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References

1. B. Clarke, D. Dimitrova et al. *A decision support system to proactively manage subsurface utilities*. International Symposium for Next Generation Infrastructure, Institution of Civil Engineers, London, 11-13 Sep, 2017. 2
2. H. Du, V. Dimitrova, D. Magee, R. Stirling, G. Curioni, H. Reeves, B. Clarke, and A.G. Cohn. *An Ontology of Soil Properties and Processes*, in Proceedings of the 15th International Semantic Web Conference (ISWC), pp. 3037, 2016. 2
3. H. Du, B. Clarke, D. Entwisle, et al. *Ontologies for describing Properties and Processes of City Infrastructure Assets: the Ground, Roads and Pipes*. University of Leeds. [Dataset] `https://doi.org/10.5518/190`, 2017. 2
4. J. Euzenat, P. Shvaiko. *Ontology matching*, 2nd edition, Springer-Verlag, Heidelberg (DE), 2013. 3
5. Q. Mahesar, V. Dimitrova, D. Magee, and A. G. Cohn. *Uncertainty Management for Rule-based Decision Support Systems*. IEEE International Conference on Tools with Artificial Intelligence (ICTAI), 06-08 Nov, Boston, USA, 2017. 4, 5
6. C.D.F. Rogers, T. Hao et al., *Condition assessment of the surface and buried infrastructure - a proposal for integration*, Tunnelling and Underground Space Technology, v(28), pp: 202-211, 2012. 2